Jet Theory

Roger Blandford

+ Maxim Lyutikov, Andrew MacFadyen....

- Observed Jets
- Fluid Jets
- Hydromagnetic Jets
- Electromagnetic Jets
- Dissipation
- Observational Discriminants

Observed Jets – History

- 82 BCE M87
- 46 BCE Cyg A
- 35 BCE 3C273
- 28 BCE 3C279
- 22 BCE NGC6251
- 21 BCE BL Lac
- 17 BCE SS433
- 15 BCE L1551
- 7 BCE 3C279
- 5 BCE GRS1915+105

Observed Jets – Chandra

- 82 BCE M87
- 46 BCE Cyg A
- 35 BCE 3C273
- 28 BCE 3C279
- 22 BCE NGC625
- 21 BCE BL Lac
- 17 BCE SS433
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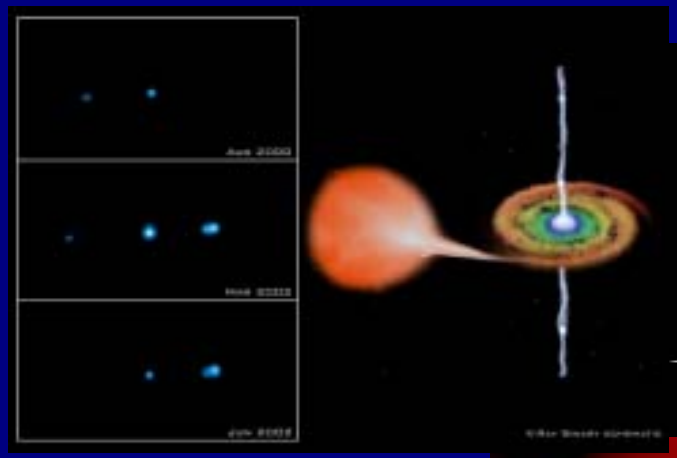
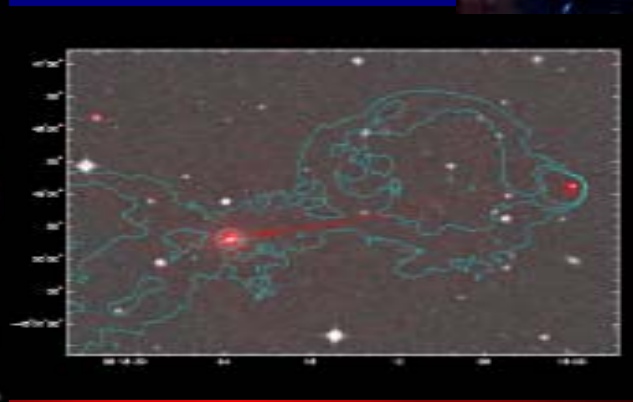
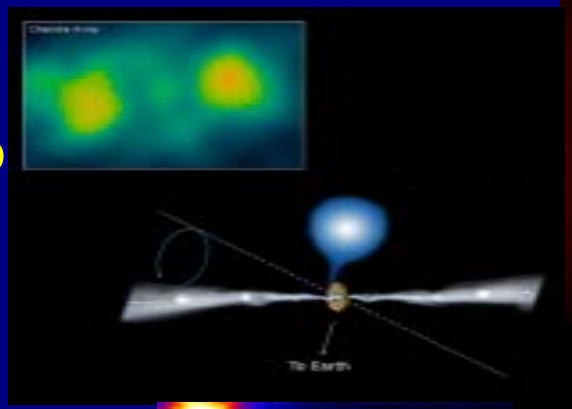
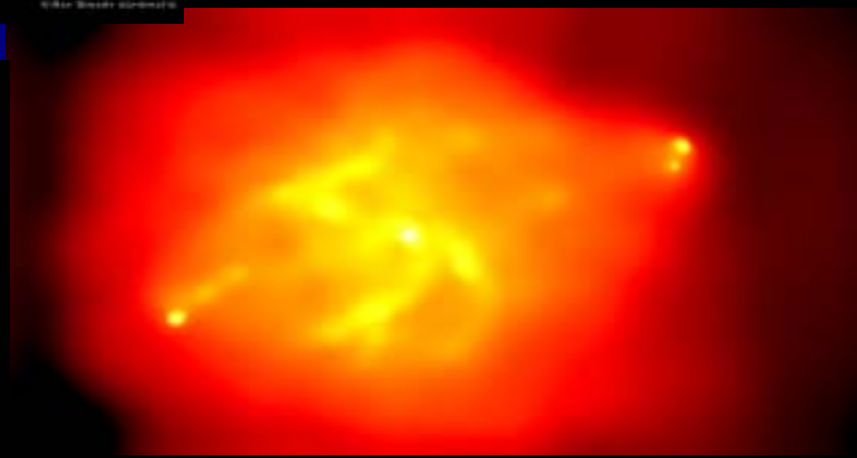
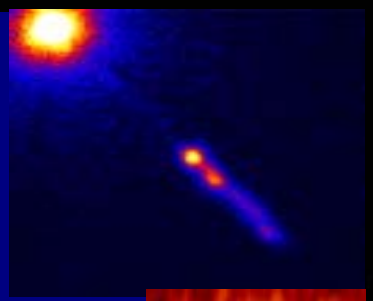
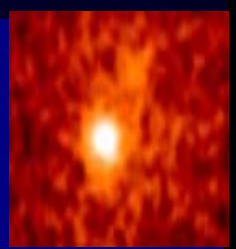


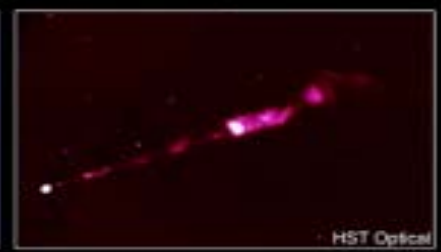








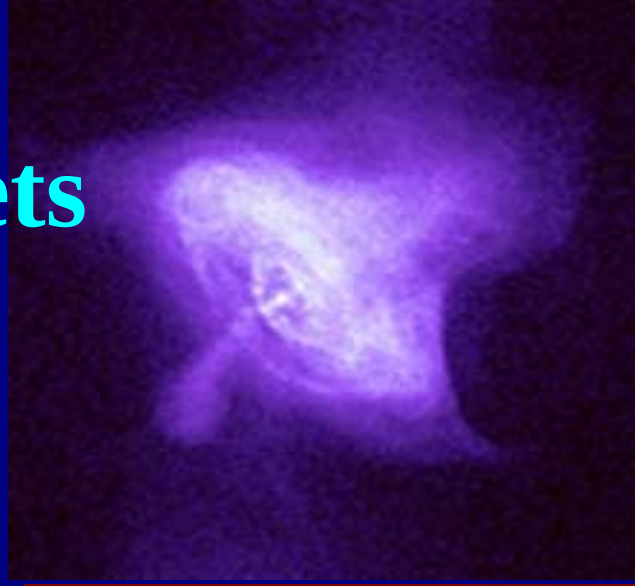




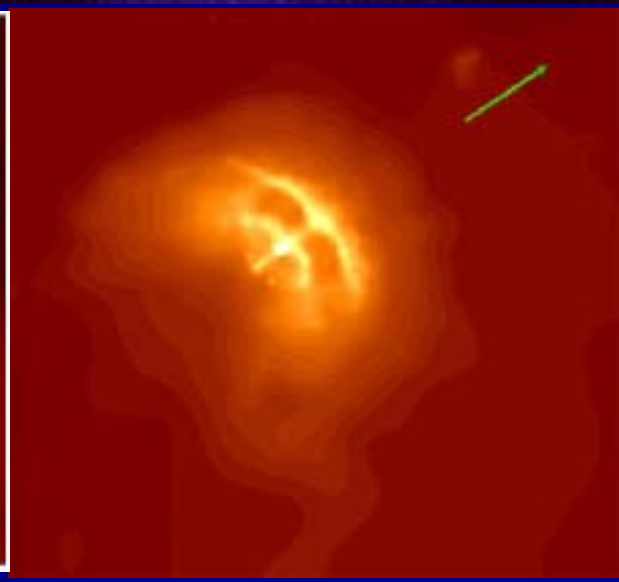
Some Wild Generalizations about X-ray jets

- Jets can be strongly collimated
- Jet powers can exceed bolometric nuclear power
- FR2 jets are relativistic, SSC, EC
- FR1 jets require continuous acceleration to100TeV
- Pair jets are more economical
- Jets can be episodic
- Jets are formed at all Eddington ratios

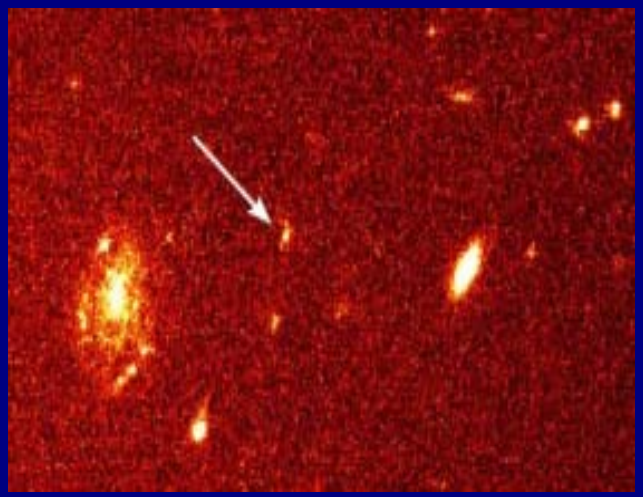
Some other X-ray Jets



- Pulsar Wind Nebulae

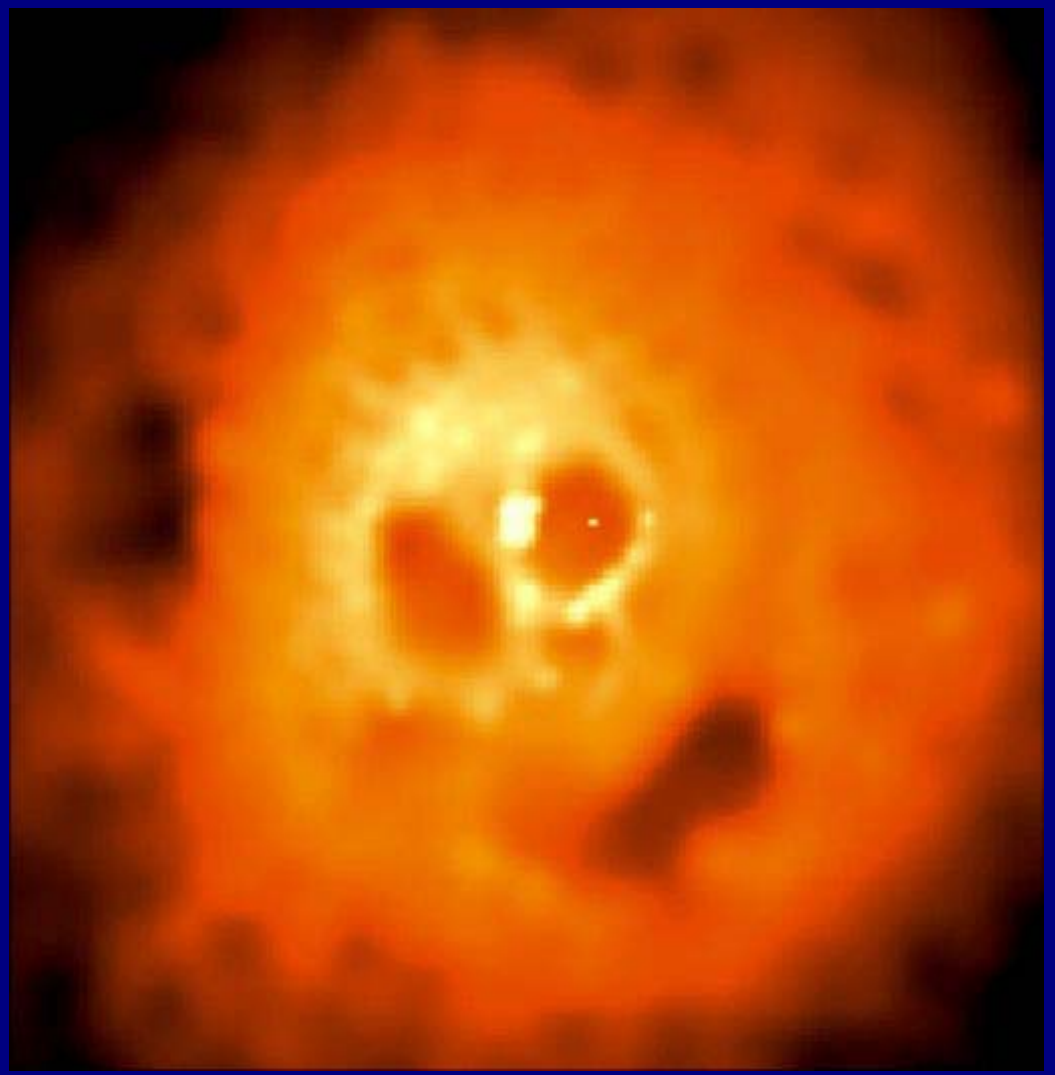


- Gamma Ray Bursts



Another Important Discovery

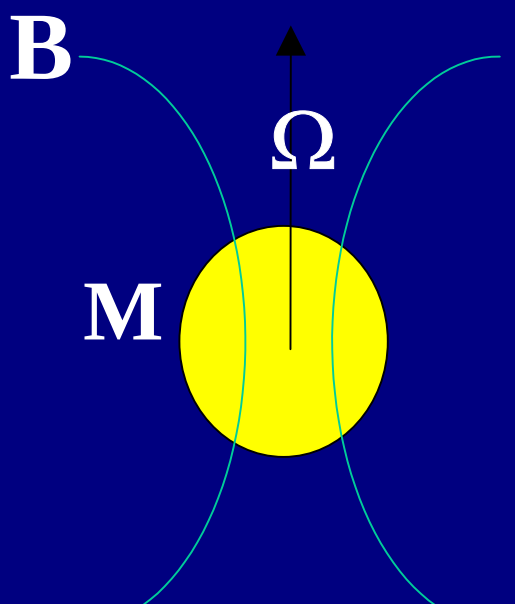
- Radio sources and hot gas do not easily mix



Sources

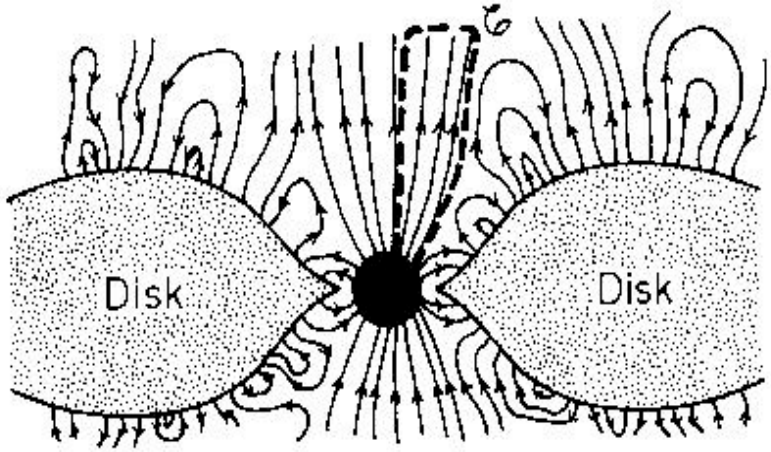
- (Hydro/electro)magnetic mechanisms for most jets
  - Protostellar jets are non-relativistic
- Galactic superluminals and some quasar jets could be radiation-driven
- GRBs could by neutrino-driven
- Fundamental mechanism is unipolar induction

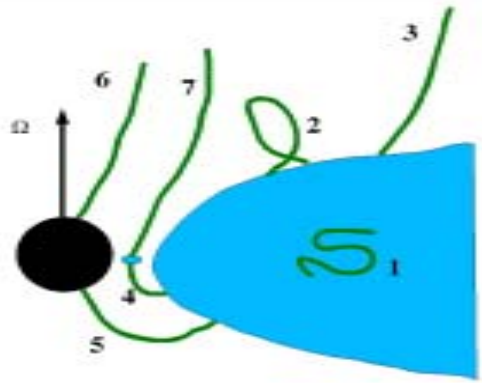
Unipolar Induction



- *Alfven 1939, Davis, Goldreich & Julian*
- Rules of thumb:
  - $\Phi \sim B R^2$; $V \sim \Omega \Phi$;
  - $I \sim V / Z_0$; $P \sim V I$

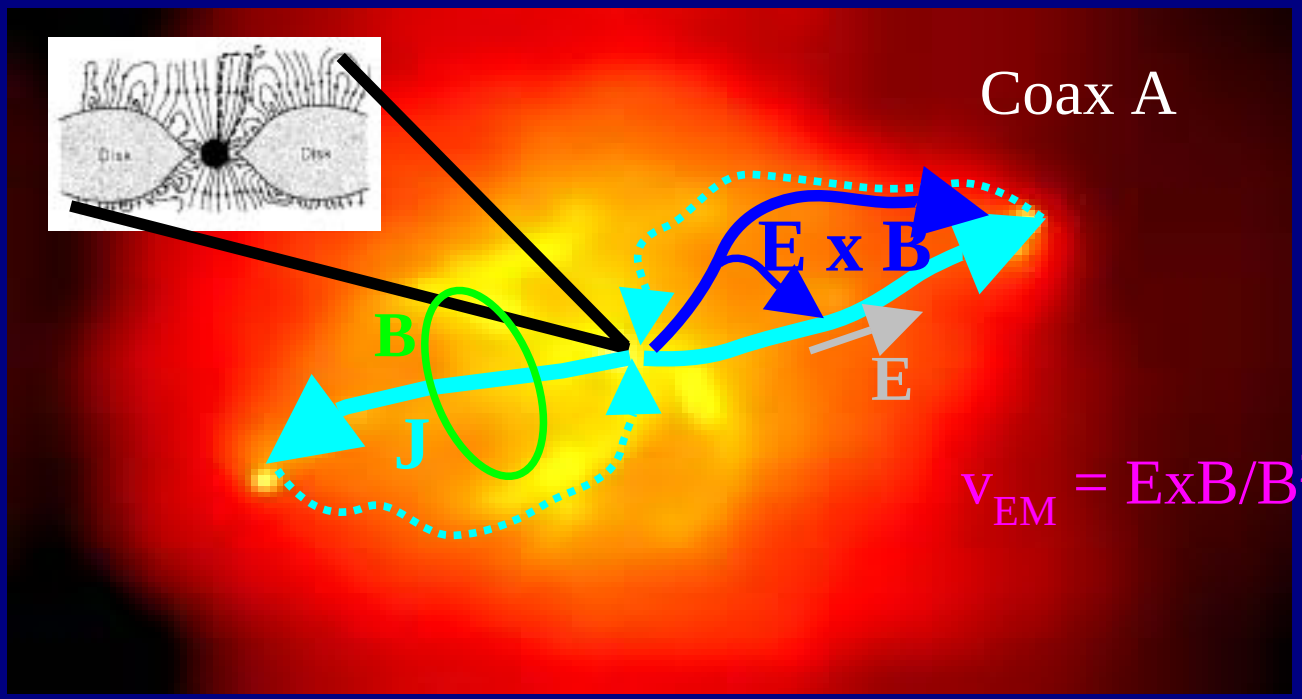
	PWN	AGN	GRB
B	100 MT	1 T	1 TT
ν	**10 Hz**	**10 μHz**	**1 kHz**
R	**10 km**	**10 Tm**	**10 km**
V	**3 PV**	**300 EV**	**30 ZV**
I	**300 TA**	**3 EA**	**300 EA**
P	**100 XW**	**1 TXW**	**10 PXW**





Currents vs Fields

- Complementary approaches B<=>j (+ boundary conditions)

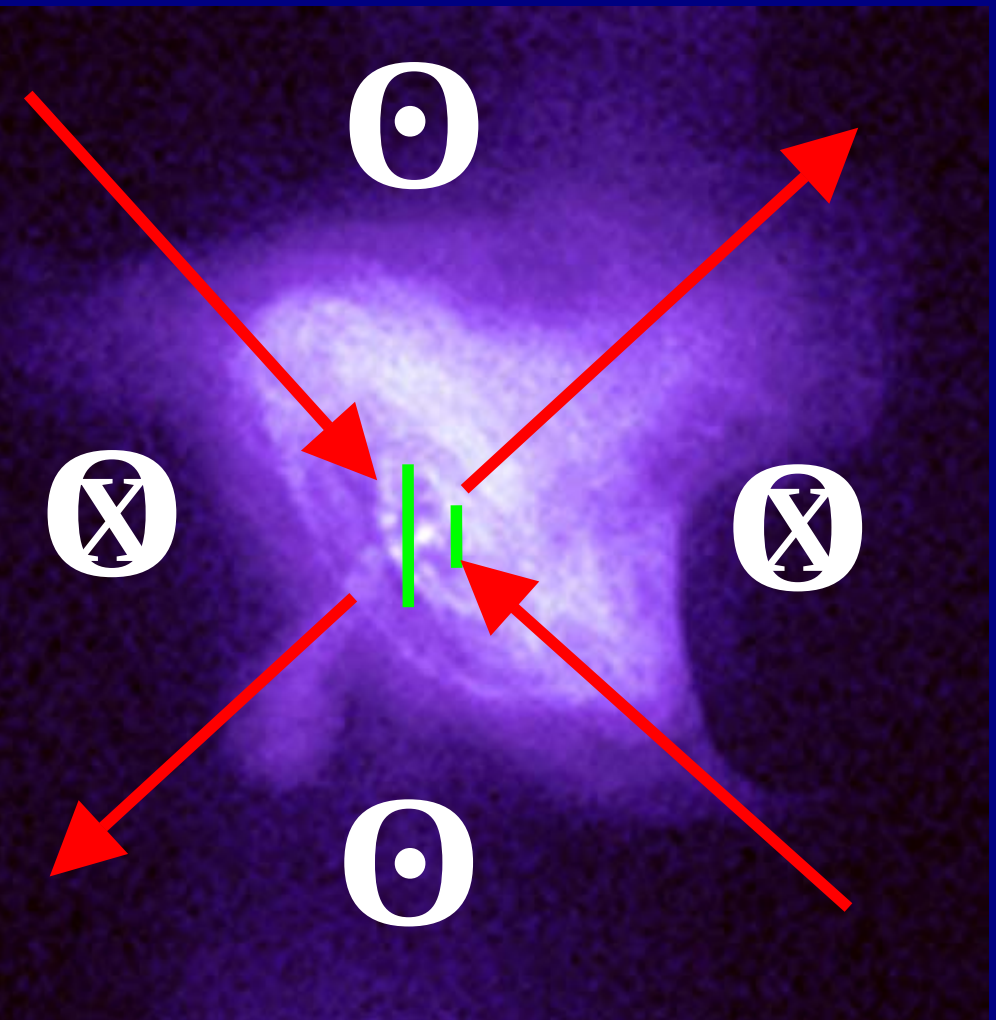


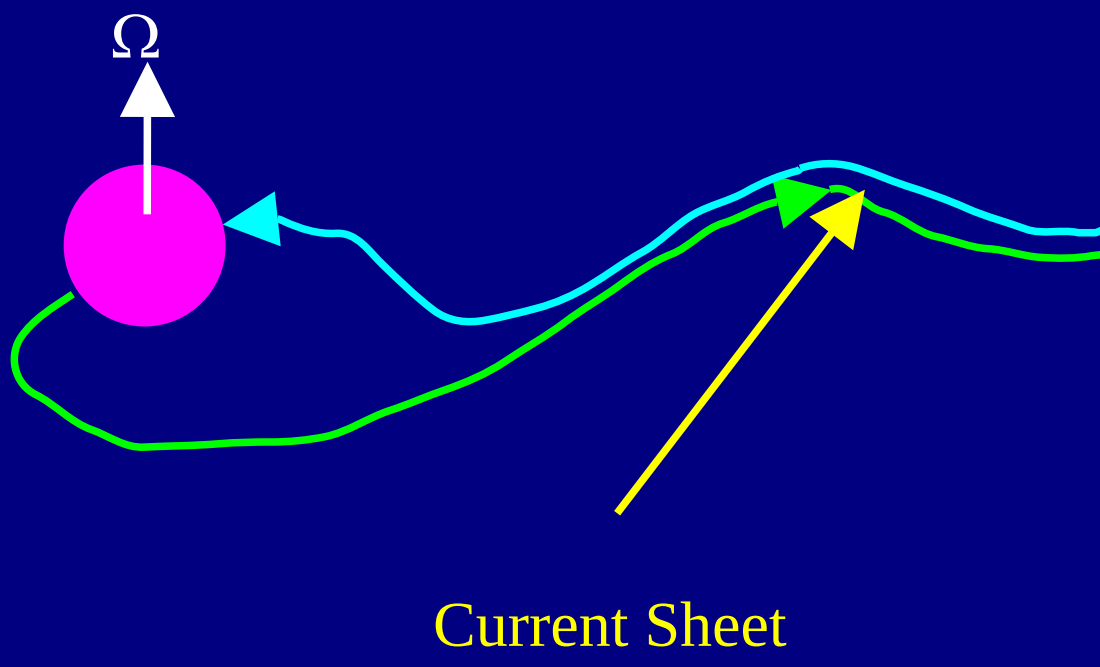
B ~ 10^{-4} G
I ~ 1EA=10^{18}A
V~ 0.1ZV=10^{20}V

- Nonthermal emission delineates dissipation of current flow
- Poynting flux carries energy, plasma and flux into and along currents
  - Line and surface currents

Pulsar Wind Nebulae

- Striped wind or axisymmetric outflow?
- Fluid or electromagnetic?



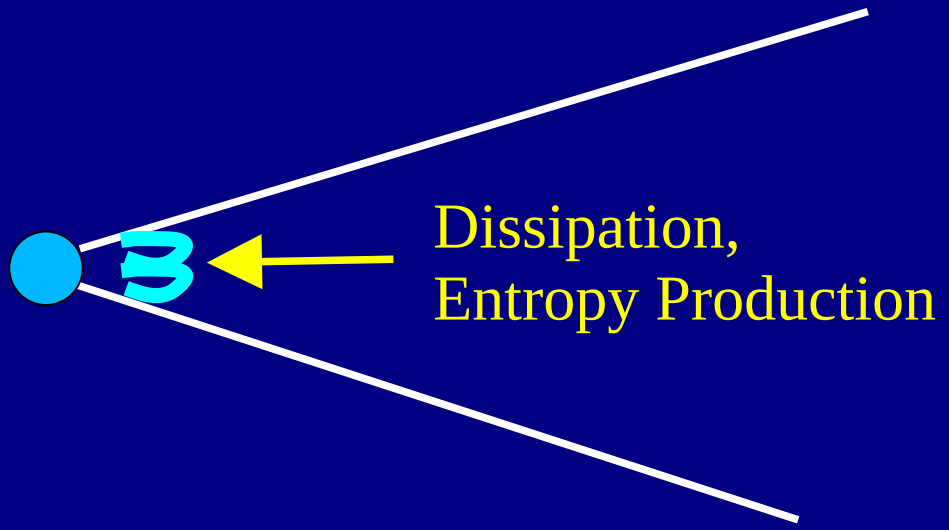


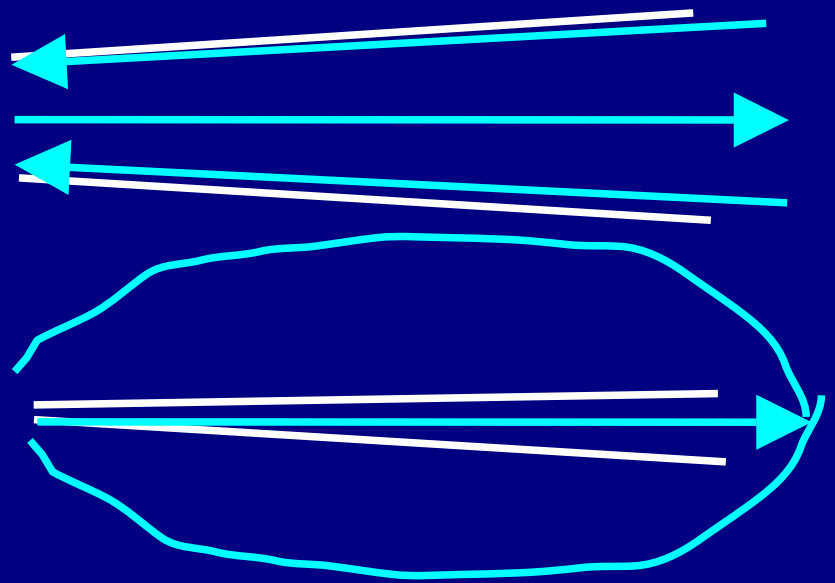
Fluids vs Fields

- Stress Energy Tensor
  - Fluid: T_F = w u x u +P g; equation of state
  - Electromagnetic:$T_M = (E^2+B^2)/2$ ExB
  - ExB BxB +ExE-$(B^2+E^2)/2$
  - ρ E+j x B=0
  - Hydromagnetic: $T_F \sim T_M$; E + v x B=0

Current Closure

- Close to source
  - massive entropy production
  - fireballs, fluid jets, PWN?
  - GRB entropy/baryon ~ 10^6k
- Jet walls
  - External Pressure $\mu_0(I/2\pi R)^2/2$
- Lobe boundaries
  - Energy reservoir
  - Lower confining pressure





Dissipation and Instability

- All jets unstable!
  - Magnetic Jets show helical instability
  - Velocity shear stabilises fluids and fields – polarization
- Fluid jets
  - internal shocks, particle acceleration, field amplification?
  - relativistic shocks – Weibel instability
  - continuous X-ray synchrotron
- (Electro)magnetic jets
  - Pinch instabilities => wave spectrum (cf MRI in disks)
  - damp on inner scale, electrostatically or wave-wave processes
  - Field becomes disordered where it is dissipative
  - magnetic stress ~ pressure => Equipartition

Mach numbers

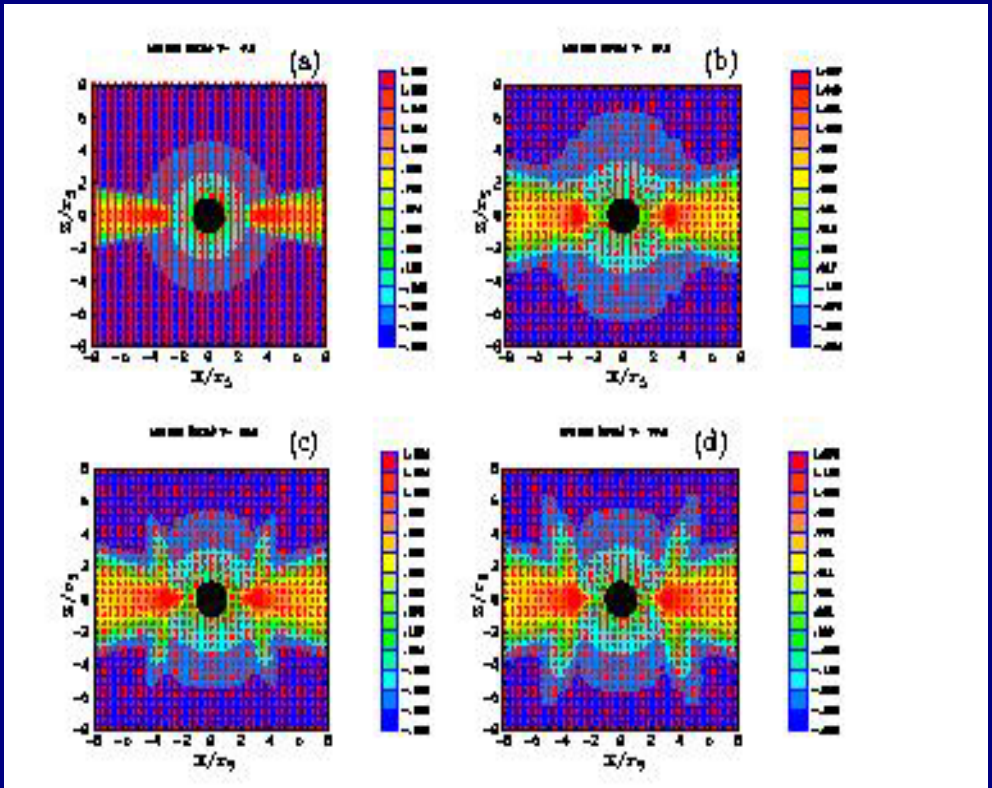
- Relativistic Fluid Jets require M ~ γ.
  - Bulk energy / internal energy ~ M^2
  - ~10^6 for GRB!
  - Strong shocks
- Electromagnetic jets
  - s ~ c ; sub or trans-sonic
  - weak or no shocks
  - nb relevant to PWN

Some Observational Discriminants

- AGN jets
  - Confirm X-ray synchrotron in M87 etc
  - Are knots, hot spots shocks? Do electrons cool
  - Helical modes?
  - FR1 vs FR2
- PWN
  - Where are the termination shocks at intermediate latitude?
  - X-ray spectral index gradients around pole, equator
- GRB
  - Polarimetry

Theoretical Approches

- Fluid/MHD/Electromagnetic simulation



Nishikawa et al

- Kinetic approaches
  - Dissipation, acceleration, amplification

Message for Sponsors

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Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)

X-ray Polarimetry Feb 9-11 2004

Beyond Einstein May 12-14 2004

Texas Symposium Dec 13-17 2004

Summary

- Chandra observations re-open some questions about the nature of jets
- Heterogeneous class
- Fluid vs MHD vs Electromagnetic descriptions
- Thinking about the current flow may be helpful
- Useful observational discriminants include spectral index maps, polarization and radio maps